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by

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ABSTRACT

The recent fracture of a large generator rotor (125,000 kw – 3600 rpm) led to an extensive investigation aimed at determining the cause. This paper describes the various facets of this investigation, the results obtained, and the probable cause of the burst.

INTRODUCTION

On March 18, 1956, the generator rotor of the 169,118-kva Pittsburg Unit No. 1, of the Pacific Gas and Electric Company, burst during an overspeed-governor trip test. This test was being made before placing the turbine-generator into operation following an inspection and overhaul of the turbine.

The Pittsburg station is an outdoor power plant having four duplicate 3600-rpm turbine-generators each rated 125,000 kw. The first of these, Unit No. 1, went into service in May 1954, and the station records showed the unit had 51 starts and stops, and 30 overspeed-governor checks, with 10 of them at or slightly above 4000 rpm. For about two months prior to the burst, it had been shutdown for a regular inspection and overhaul. During the shutdown, ambient temperatures dropped to 40-50 F. In starting again, the rotor was overspeeded three times to check and set the emergency trip, and it was run intermittently at no load or light loads from the morning of March 17, to the evening of March 18, when, while checking the overspeed trip again, the rotor burst at 3920 rpm. The broken pieces of the rotor were contained within the stator. There was some damage to the turbine caused by a sudden end thrust resulting from jamming of the generator rotor fragments. The turbine was repaired, and with a replacement generator, the unit went back into operation four months later.

GENERAL DESCRIPTION OF FRACTURE

The rotor body burst lengthwise into two half-cylinders like a log split down the middle. The two halves then broke into smaller pieces. Figure 1 is

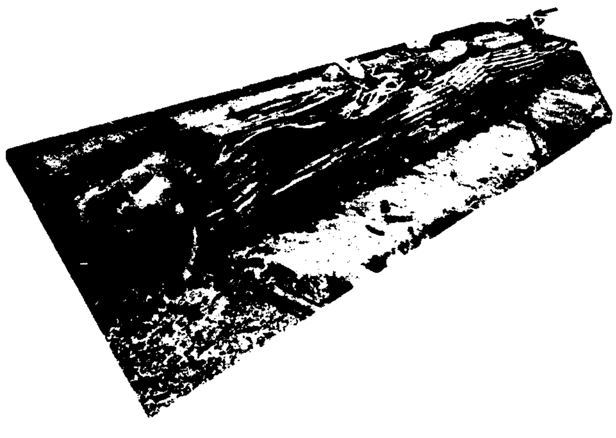

Fig. 1. View of burst rotor after removal of upper half of stator frame and core

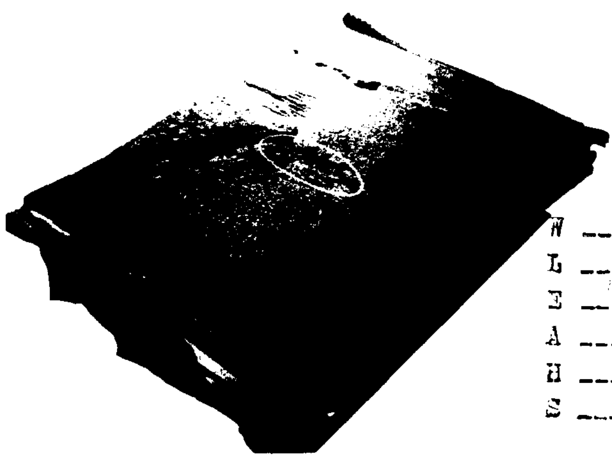

Fig. 2. Photograph of segment near exciter end containing fracture origin; encircled portion is 2-in. x 5-in. woody area

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a photograph of the field exposed after cutting away the top-half of the stator.

Visual examination of the fractured surfaces as the fragments were removed from the stator indicated that the origin of the burst was located in one fragment, about ten feet long, of the main body. The origin of the fracture was an area about 5 inches long axially by 2 inches wide radially, located about 30 inches from the collector end of the body and nearly on the axis. This 2-in. x 5-in. area had a "woody" or fibrous appearance different from that of the fracture surface surrounding it. The presence of fracture striations emanating from this "woody" area indicated that this was the origin of the fracture. Figure 2 is a photograph of a portion of the primary fracture surface containing the 2-in. x 5-in. area. As can be seen, there is no evidence of the common fatigue striations that would be present if this 2-in. x 5-in. area had increased in size by fatigue progression.

At the time the 10-ft section was removed from the stator, clusters of greenish-yellow particles typical of silicate-type inclusions were observed in the center of the 2-in. x 5-in. area. Apparently these particles were embedded in the coating used to protect the fractured surfaces during transit to the factory for investigation and subsequently removed during the cleaning operation.

FORGING MANUFACTURE AND PROPERTIES

As received from the mill, the forging weighed approximately 95,000 pounds, was about 35 feet long with a main body 39 5/8 inches in diameter and 19 feet 8 inches long. The acid open-hearth ingot, from which it was made was 92 inches in diameter and weighed about 249,000 pounds.

Chemical analysis as determined at the ladle and reported in the vendor's Certificate of Test conformed to the specification requirements. These data are presented in Table 1.

The mechanical hot-working operation consisted of forging from a 92-in. corrugated ingot to a 65-in. diameter cylinder, then cropping 35 percent from the top and 10 percent from the bottom of the ingot, and finish forging in the range of 2200-1500 F. All forging operations were performed under a 7500-ton press.

The ingot was subjected to a protective thermal treatment to prevent flaking or cracking during the hot-work operation.

Due to a pending strike at the steel mill, the usual practice of double normalizing following by tempering was modified to permit storing the forging. The heat treating sequence consisted of a normalize from 1640 F, and a temper at 1200 F prior to the strike. When work was resumed, the forging was given a final normalize at 1550 F and a double temper at 1200 and 1220 F respectively. It was stress-relieved at 1100 F after rough machining. The complete thermal cycle is presented in Fig. 3.

The mechanical properties of test specimens from the body and prolongation areas as reported by the vendor are presented in Table 2. They are superior

TABLE 1

PITTSBURG ROTOR CHEMICAL COMPOSITION

			Radial Location from Center					
			1.5 – 3 in.		11 in.		Surface	
Element	Specification	Ladle Analysis	Turbine End	Collector End	Turbine End	Collector End	Turbine End	Collector End
C	0.32 max	0.26	0.22	0.27	0.23	0.24	0.24	0.25
Mn	0.90 max	0.67	0.64	0.67	0.63	0.65	0.63	0.66
P	0.05 max	0.028	0.024	0.029	0.025	0.026	0.028	0.022
S	0.05 max	0.027	0.024	0.028	0.023	0.023	0.023	0.024
Si	0.15 – 0.35	0.25	0.18	0.22	0.21	0.24	0.25	0.21
Ni	2.50 min	2.88	2.85	2.95	2.86	2.92	2.82	2.91
Mo	0.40 min	0.54	0.48	0.57	0.50	0.55	0.49	0.54
Cr	0.50 max	0.34	0.35	0.34	0.34	0.34	0.34	0.32
V	0.03 min	0.07	0.06	0.06	0.05	0.07	0.05	0.07
Cu	Not specified	–	0.31	0.30	0.30	0.35	0.29	0.32
S_b	Not specified	–	nil	nil	nil	nil	nil	nil
A_s	Not specified	–	0.009	0.012	0.012	0.010	0.012	0.010
*H_2	Not specified	–	1.9	1.7	1.1	–	–	–
*(Parts per million by weight)								

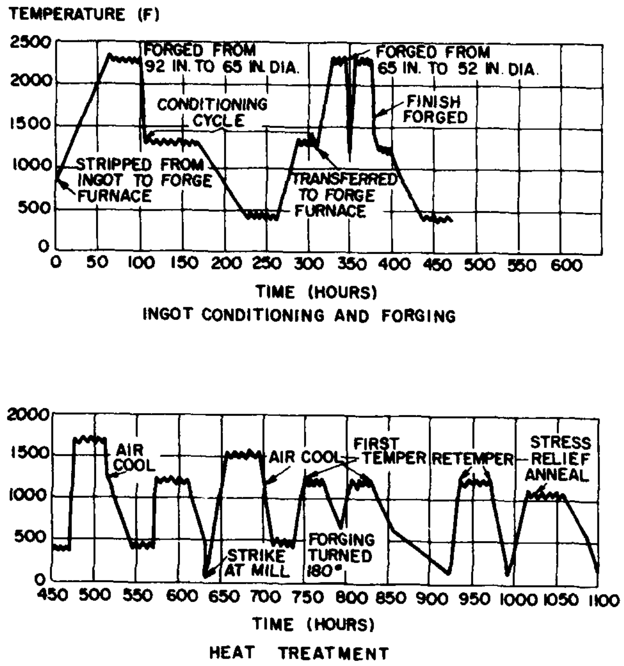


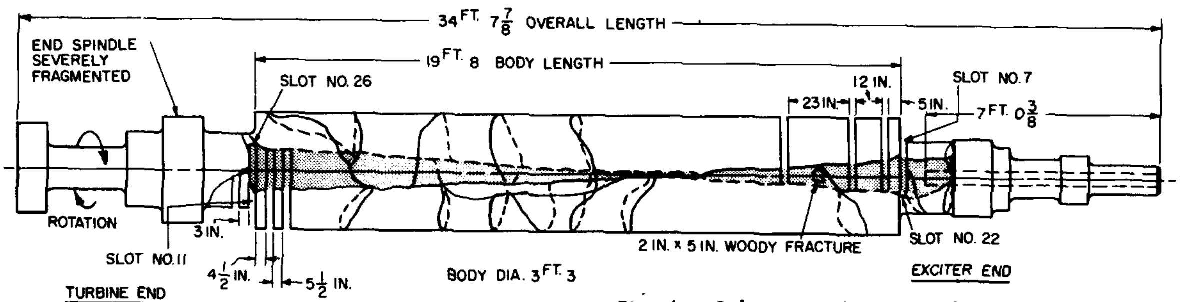
Fig. 3. Complete thermal cycle

to the requirements as designated in the specification. Included in Tab 2 are the keyhole Charpy impact results which were obtained by the steel mill for information purposes. The energy absorbed in fracturing these bars indicates a relatively high insensitivity to moderate notches.

Ultrasonic examination of the forging prior to service disclosed the presence of several scattered indications at 5 to 25 percent magnitude in the exciter end of the main body and exciter-end spindle. All indications were located near the center of the forging.

CHECK TESTS OF ROTOR FRAGMENTS MATERIAL

To ascertain if there were any abnormalities in the rotor (obviously not apparent in the acceptance tests results) which might explain the low average-stress-level burst, numerous tests, such as mechanical, notched bend, fatigue and others, were obtained on specimens from the rotor fragments. The locations of the fragments discussed in this paper are shown in Fig. 4. A brief summary of these test results follow.



NOTES: (1) SHADED AREA:-PRIMARY FRACTURE SURFACE, A WARPED PLANAR SURFACE ROUGHLY PERPENDICULAR TO A DIAMETER THROUGH THE POLE FACES AND DIVIDING THE FIELD INTO APPROXIMATELY EQUAL HALVES.
(2) TRANSVERSE SECONDARY FRACTURES ARE ONLY APPROXIMATELY LOCATED.

Fig. 4. Schematic diagram of the Pacific Gas and Electric No. 1 generator rotor showing the locations of primary longitudinal fracture, the major transverse fracture, and locations of test segments

TABLE 2

PITTSBURG ROTOR ACCEPTANCE TESTS FOR MECHANICAL PROPERTIES

	Location	Test Direction	Tensile Strength (psi)	Yield Strength (0.02 Percent Offset)	Percent Elongation (2-inch Gage Length)	Percent Reduction of Area	Keyhole Charpy (ft-lb)
Specification	Prolongation	Longitudinal	100,000	75,000	17.0	32.0	–
	Body	Radial	100,000	75,000	13.0	22.0	–
Acceptance Test Results	Prolongation	Longitudinal	100,000	79,500	24.0	64.7	39,35
	Mid-body	Radial	100,000	78,250	20.5	47.7	–
	End-body	Radial	112,000	90,500	16.5	35.7	–

A-1

TABLE 3

TENSILE TESTS ON FRAGMENTS FROM MAIN BODY

Location: Rotor	Location: Fragment	Test Direction	Test Condition	Tensile Strength (psi)	Yield Strength (0.02 Percent Offset)	Percent Elongation (2-inch Gage Length)	Percent Reduction of Area
43 – 48 in. from Exciter End of Body	Surface	Longitudinal	A*	90,000	78,500	23	62
			U**	97,500	78,000	22	56
		Radial	A	97,400	77,300	21	53
			U	97,000	77,000	16	27
		Tangential	A	97,800	77,500	20	43
			U	97,100	73,300	17	35
	11 in. from Center	Longitudinal	A	98,600	62,300 (a)	22	61
			U	98,500	41,300 (a)	20	43
		Radial	A	99,800	75,000	19	45
			U	98,400	68,500 (a)	14	25
		Tangential	A	98,000	75,000	18	43
			U	98,100	69,000 (a)	13	22
	1.5 – 3 in. from Center	Longitudinal	A	103,900	79,300	21	55
			U	102,800	79,500	18	37
		Radial	A	102,900	75,500	12	15
			U	100,500	71,500	6	6
		Tangential	A	102,500	77,500	14	23
			U	98,700	75,000	5	7
6 – 11 in. from Turbine End	Surface	Longitudinal	A	110,800	92,500	19	58
			U	111,000	93,300	18	52
		Radial	A	111,000	92,300	16	42
			U	110,400	91,500	13	23
		Tangential	A	111,000	93,000	15	37
			U	110,300	92,800	10	20
	11 in. from Center	Longitudinal	A	105,800	85,300	21	60
			U	105,800	86,800	17	46
		Radial	A	104,800	84,500	17	41
			U	104,700	84,300	12	21
		Tangential	A	105,200	85,000	18	48
			U	105,500	85,000	12	23
	1.5 – 3 in. from Center	Longitudinal	A	105,500	85,500	21	60
			U	107,400	87,800	15	35
		Radial	A	105,600	86,000	14	29
			U	105,700	88,000	8	9

(a) Test bars obtained from portion of fragment which shows severe mechanical deformation as a result of burst.

* Aged tensile bar

** Unaged tensile bar

CHEMICAL ANALYSES

Analyses of material from various radial and axial locations in the fractured segments are included in Table 1, and show excellent uniformity of alloy content throughout the forging.

MECHANICAL PROPERTIES

Results of the aged and unaged tensile tests from several axial and radial locations are tabulated in Table 3. The mechanical properties determined are typical of those found in other Ni-Mo-V forgings similarly examined. Table 3 includes tests on four bars removed from material which had received severe deformation immediately following the fracture. These four bars show lower yield strengths than the others. This can be expected, since it is known that such severe deformation may depress yield strength. The decline in ductility from surface to bore as exemplified in the unaged tensile bars is common in large forgings of the Ni-Mo-V composition made from ingots melted and poured in air.

NOTCH SENSITIVITY

Impact Tests

Subsequent to the burst, impact tests were made on 45-degree V-notch Charpy specimens taken from near the center and near the outer surface of the rotor from both the turbine and exciter ends of the main body.

The energy absorbed and fracture appearance of the Charpy specimens over a range of temperature is presented in Fig. 5. These results show a variation in fracture-appearance transition temperature with location in the forging which is summarized in Table 4.

The main-body temperature was estimated as about 85 F when the forging burst, and at this temperature the center material at the exciter end has a V-notch Charpy impact value of 7 ft-lb, indicating relatively low resistance to crack propagation.

TABLE 4

	Exciter End		Turbine End	
	Bore	Surface	Bore	Surface
50-percent Fracture Appearance Transition Temperature (F)	210	155	170	195
Energy Absorbed at Transition Temperature (Ft-lb)	22	35	22	21

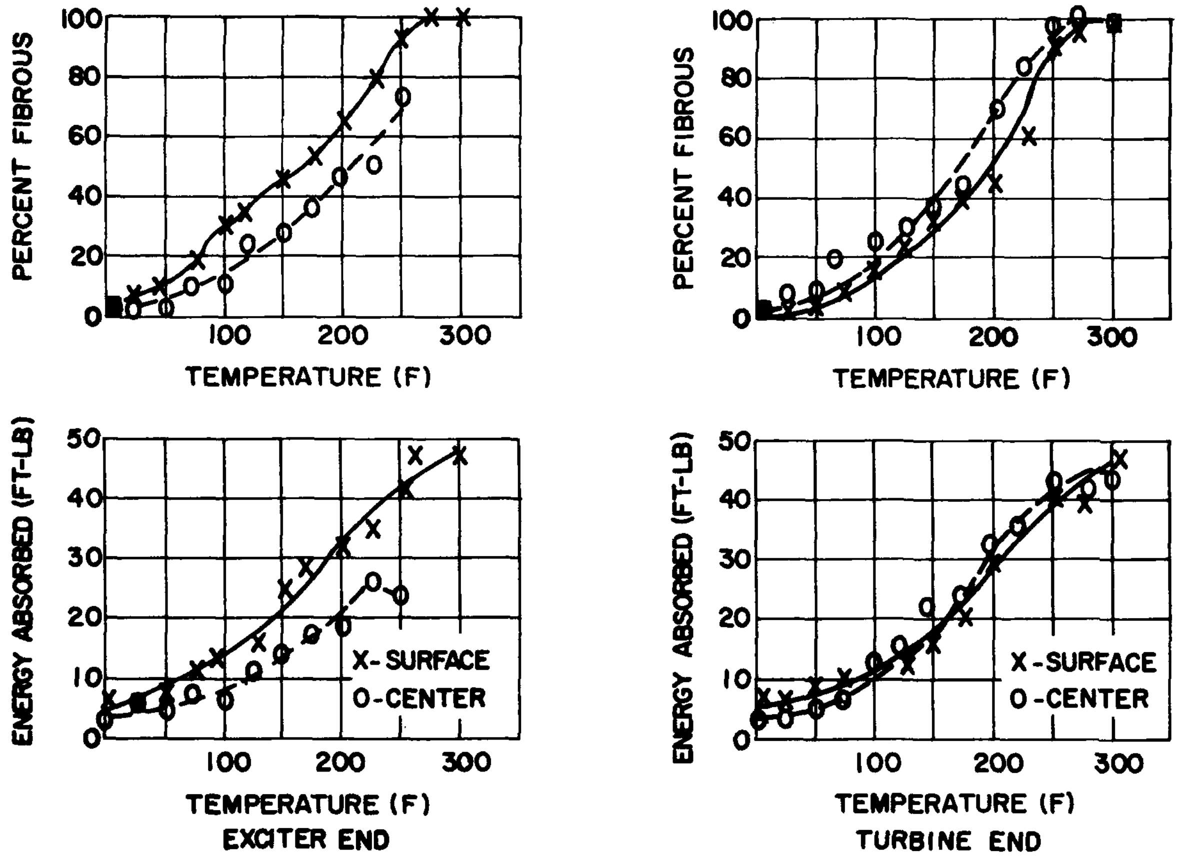


Fig. 5. Charpy V-notch impact-energy and fibrous-appearance curves

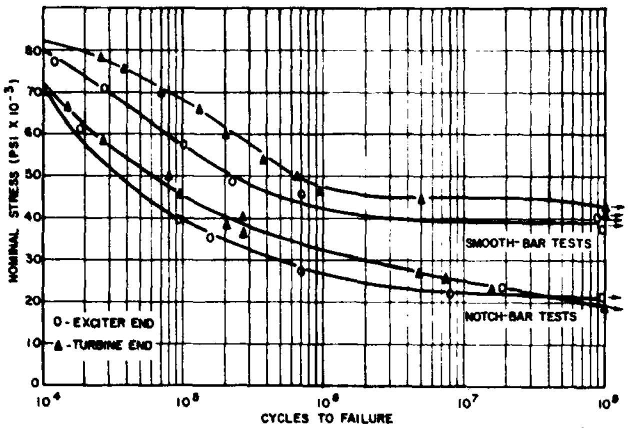


Fig. 6. Smooth and notched-bar fatigue strength

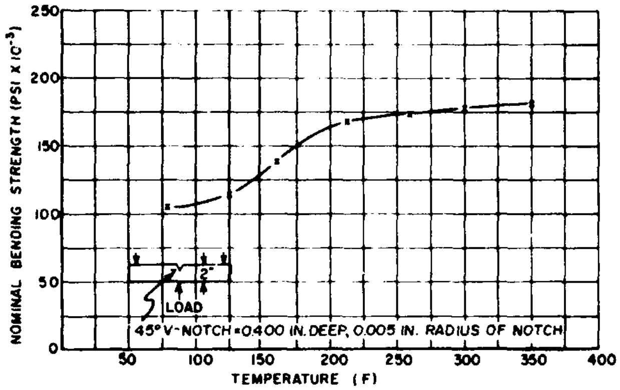


Fig. 8. Temperature dependence of notched-bend strength

Fatigue Test

Fatigue test results from smooth- and notched-bar cantilever specimens, in the radial direction of material from the exciter and turbine ends of the forging body are shown in Fig. 6. The cross-section of the smooth bar was 0.343 inch x 0.625 inch. The notched bars were 0.493 inch x 0.625 inch, with two notches 75 mils deep giving a net section the same as the smooth bar. The radius at the bottom of each notch was 20 mils. This gave a theoretical stress concentration factor of approximately 2.6. The 10^8-cycle smooth-bar fatigue strength is 37 percent of the tensile strength at the exciter end and 40.7 percent at the turbine end, while the notched fatigue strength is 20.7 and 18.7 respectively. These results are similar to those obtained on several other large turbine and generator rotors so far examined.

Slow-bend Tests

Slow-bend tests were made to more nearly simulate the tri-axial stress pattern, which may exist in the vicinity of internal discontinuities in the rotor under operating conditions. The notched specimens were broken by loading slowly in simple bending. These 45-degree V-notch specimens had a constant-notch radius of 0.005 inch and varied in size from 3/16-in. to 3-in. square. Test results from mid-radius locations at the exciter and turbine ends of the main body are shown in Fig. 7.

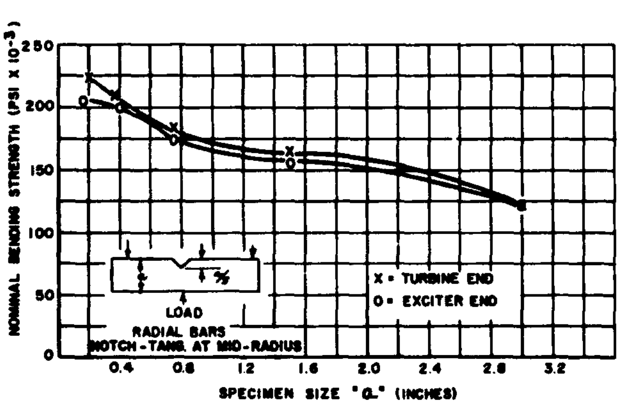


Fig. 7. Notched-bend strength, Pacific Gas and Electric rotor No. 1

Here nominal bending strength is merely the product of bending moment at fracture times the inverse-section modulus of the net section at the root of the notch. It will be noted that bending strengths of the notched bars decrease with increasing size of bar. Although the data presented were obtained at ambient temperatures, it has been found that the nominal bending strength of larger notch-bend specimens from similar material increased quite rapidly with moderate increases in temperature. Typical results are shown in Fig. 8. The material at the exciter end of the main body shows lower nominal bending strength than at the turbine end.

Additional slow-bend tests were performed on standard Charpy V-notch specimens from various radial positions in the fracture origination fragment. These tests showed a nominal notch-bend strength 12 percent higher at the outer surface than at the center.

This is consistent with the V-notch Charpy tests on material from the same general location in the rotor. Therefore both types of tests show the center material at the exciter end of the main body has greater sensitivity to stress concentration than material near the outer surface.

While the stress levels required to produce fracture in the various notched-bend specimens are considerably higher than the stress of 24,000 psi which existed at the solid center of the Pittsburg rotor at 3920 rpm, these notch-bend tests do show decreased load-carrying ability with increase in specimen size; and further, that the material fractures rather than deforms in relieving severe localized stresses.

INTERPRETATION OF ULTRASONIC TEST

Original sonic examination had indicated there were only two minor indications up to 25 percent in magnitude in the vicinity of the fracture origin. From calibration of our sonic-test equipment, a 25-percent indication shows the presence of something no larger than a dime. It was concluded that the sonic indications were the result of small slag inclusions and the forging was accepted. This conclusion was consistent with the sonic-test acceptance standards as presented by Messrs. Rankin and Moriarty to the ASME in December 1955, in the paper "Acceptance Guide for the Ultrasonic Inspection of the Large Rotor Forgings." Figure 9 shows the approximate location of the number-magnitude line of the Pittsburg No. 1 forging plotted with our so-called "inner and outer lines" from Fig. 12 of that paper. In cutting up nine rotors, and in the examination of 87 trepans from 30 other rotors, we had never found cracks nor other harmful defects in a forging whose number-magnitude line lay within the outer line and on which there were no traveling indications. The inner line was drawn parallel to the outer line at half the number and magnitude level of the outer line to define a region within which there appeared to be a high degree of certainty that no cracks or other harmful defects existed, based on all of our experience. As shown on this chart, the Pittsburg No. 1 rotor lies well within the inner line. In addition, there were no traveling indications. By sonic test, and by all the standards and experience available, this was judged to be a sound and serviceable forging.

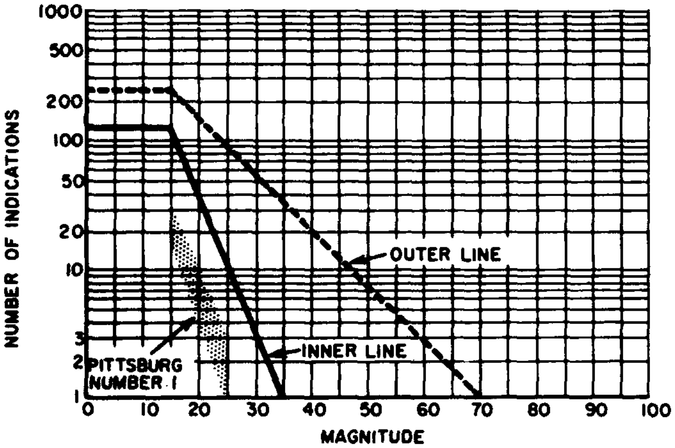


Fig. 9. Sonic-acceptance guide lines

METALLURGICAL STUDY OF FRACTURE SURFACE

Figure 10 is a closeup photograph of a portion of the 2-in. x 5-in. area from which the fracture apparently started. Many thin transverse sections were cut through this area and mounted so that the surface of this area could be examined under a microscope. In addition, many similar specimens were obtained for examination of the fracture surface outside of the 2-in. x 5-in. area. Under the microscope, the differences between the surface in the 2-in. x 5-in. area and the fracture outside of this area are quite pronounced. In the 2-in. x 5-in. area, the surface is predominantly intercrystalline. Outside this area, the fracture is transcrystalline, with secondary transcrystalline shatter cracks adjacent to the fracture. Figure 11 is a photomicrograph showing an intercrystalline separation in the 2-in. x 5-in. area, while Fig. 12 is a photomicrograph of a transcrystalline fracture found outside of the 2-in. x 5-in. area.

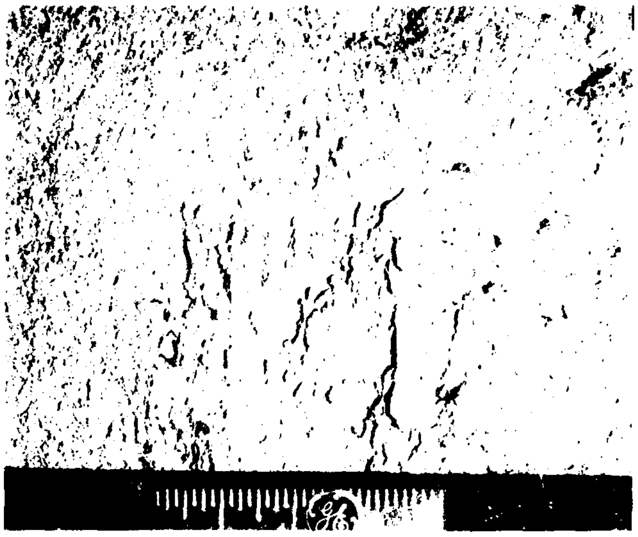


Fig. 10. Closeup photograph showing one portion of the 2-in. x 5-in. woody area (encircled)

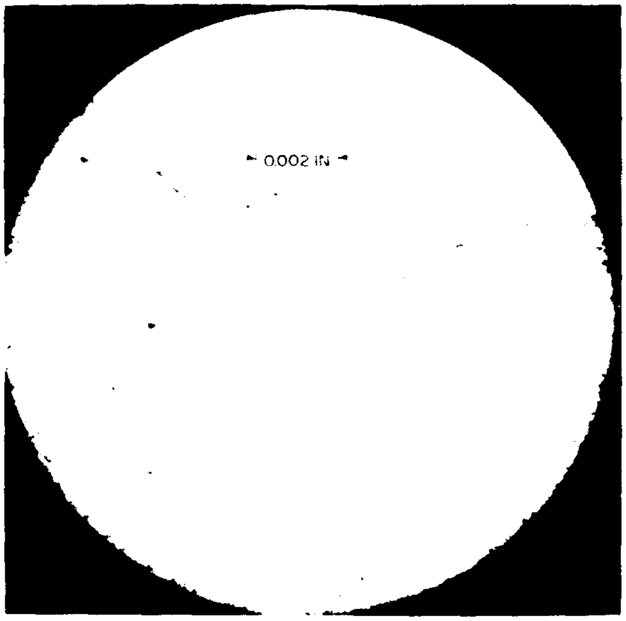


Fig. 11. Photomicrograph showing intercrystalline fracture in 2-in. x 5-in. woody area

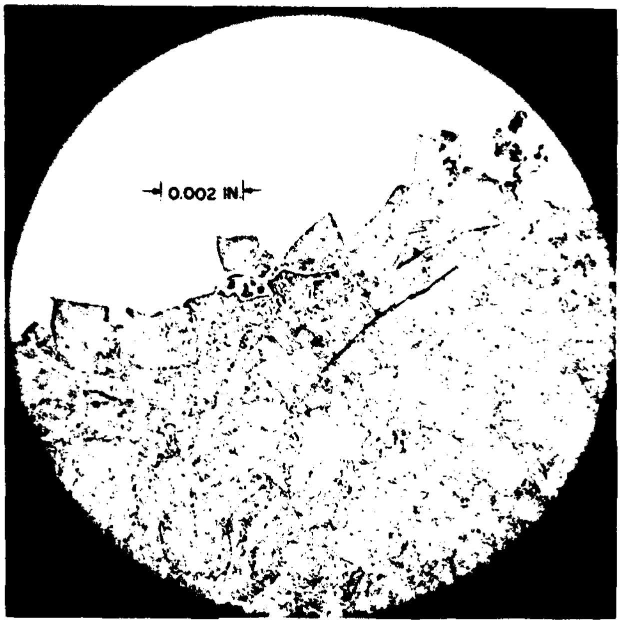


Fig. 12. Photomicrograph depicting transcrystalline fracture outside woody area

We interpret these observations as follows: First, the presence of secondary transcrystalline shatter-cracking is characteristic of a rapidly progressing cleavage-type fracture, and its absence indicates some different mode of separation. Second, low-temperature fractures are normally transcrystalline. Intercrystalline surfaces are usually formed by solidification from the melt, or by fracture at high temperature, or by fracture at low temperature followed by heat treatment at a sufficiently high temperature, to produce recrystallization. This forging was never heated to the recrystallization temperature after we received it. Therefore, the intercrystalline surface and the absence of secondary transcrystalline shatter-cracking in the 2-in. x 5-in. area indicate that most of this surface existed in the forging when it was received in our factory.

The difference between the size of the discontinuity in the rotor deduced from macro and micro study of the 2 in. x 5 in. area, as compared to that indicated by the sonic test appears to be resolved recently by the results of an investigation of another generator rotor after about two-year's service in the Unit No. 3 at Pittsburg station.

CHANGE IN SONIC INDICATIONS IN PITTSBURG NO. 3

A sonic test of that rotor at the station last October, after about two-years service, showed indications different from those observed during manufacture, when we had recorded 10 to 15 indications of 5- to 10-percent magnitude near the axis of the rotor in a region 18 inches to 38 inches from the turbine end of the body. The later test after service showed an indication of 40-percent magnitude in this same locality. Moreover, the magnitude increased to this value as the crystal was traversed circumferentially from one edge of the pole to the other, suggesting that a still larger indication would have been observed if it had been possible to extend the traverse over into the slotted region, which we were not able to do with the equipment available then. This was the first time we had found a change in the sonic-test results after a rotor was run, and we had re-tested 17 rotors after they had been in service.

METALLURGICAL EXAMINATION OF SONIC INDICATION IN PITTSBURG NO.3

A 3 1/4-in. diameter hole was bored through the center of this rotor, and in the process a trepanning tool was used to remove a core 2 3/8 inches in diameter and 32 inches long in the vicinity of the sonic indication. This was found to contain a nearly continuous array of complex magnanese silicate inclusions lying in a more or less flat plane near the axis of the rotor, and covering an area about 1 1/2 inches by 8 inches. A model of the surface formed by the non-metallic inclusions is shown in Fig. 13. The bore surface was free from inclusions, porosity, etc. when examined visually and by magnetic particle test, and the rotor returned to service.

Figure 14 is a photograph of the face of a transverse slice cut from the trepanned bar. A transverse section of the 1 1/2-in. x 8-in. plane of inclusions can be seen contained within this slice. Figure 15 is a photomicrograph of one of the thickest sections of inclusions which tapers gradually to the very thin extremities as shown in Fig. 16. The surface of the metal in contact with the plane of inclusions is intergranular, and appears similar to that found along the surface in the 2-in. x 5-in. area of the Pittsburg No. 1 rotor.

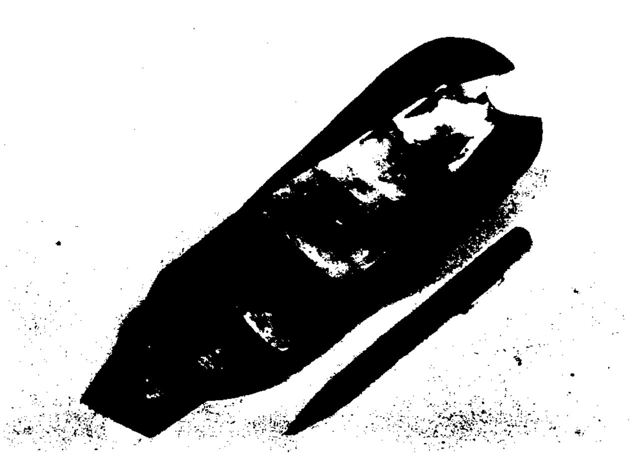


Fig. 13. Surface formed by the non-metallic inclusions (light area)

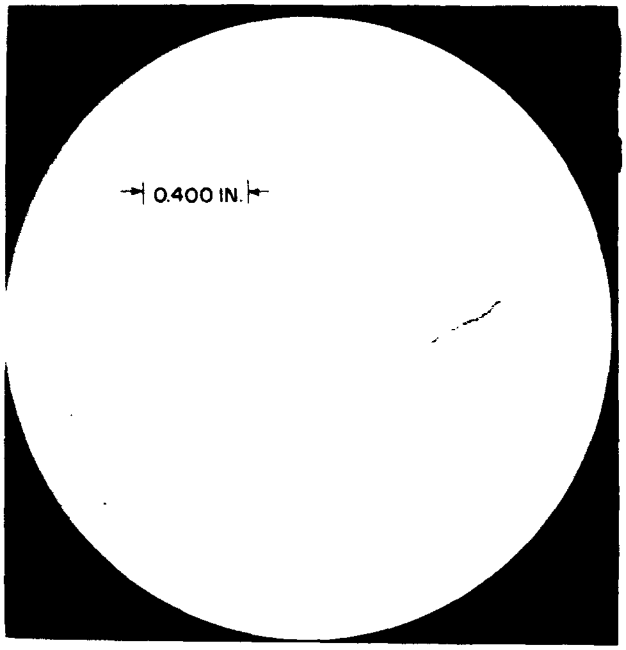


Fig. 14. Photomicrograph of cross section of 2⅜-in. diameter center-core trepan containing plane of non-metallic inclusions

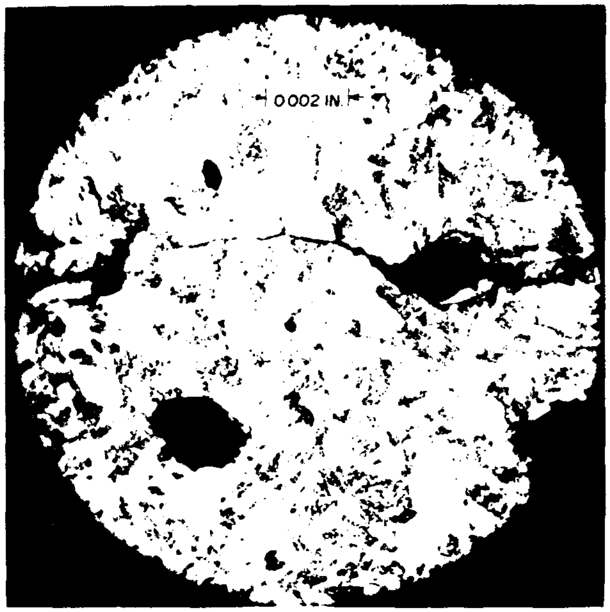


Fig. 16. Photomicrograph of the extremities of the inclusion array and surrounding structure

The inclusions were found to be bonded to the metal in some places and not in others. A section from the trepanned bar containing about 2 square inches of the inclusion complex was pulled apart. Figure 17 is a photograph of one of the surfaces after the section was pulled apart. This surface is similar to the surface in the 2-in. x 5-in. area of No. 1, but of a finer texture. Numerous cylindrical filaments of complex manganese silicates having a somewhat crystalline appearance and greenish-yellow tint could be seen with a binocular microscope, but the thin extremities connecting these filaments were not resolvable.

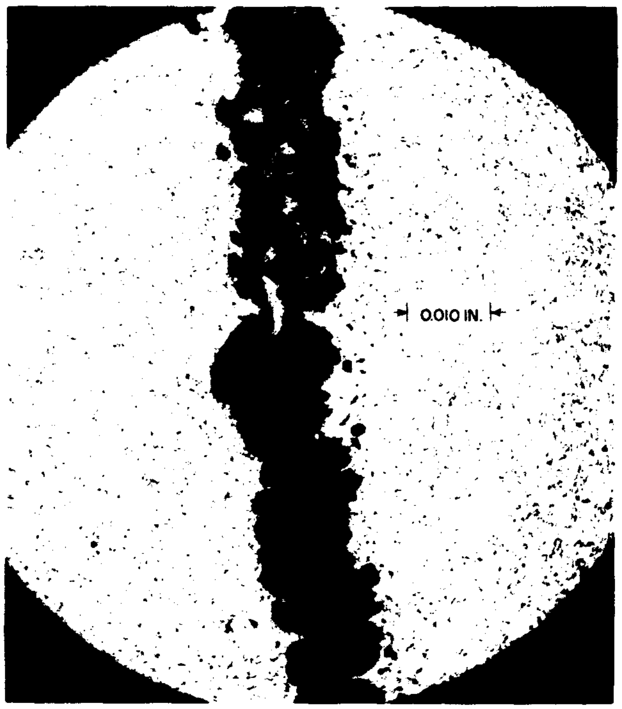


Fig. 15. Photomicrograph of a thick portion of the non-metallic inclusion array and surrounding structure

Fig. 17. Photomicrograph of one portion of fracture surface across the plane of non-metallic inclusions

SIMILARITIES OF PITTSBURG NO. 1 AND NO. 3 ROTORS

It is reasonable to believe that an array of inclusions existed originally at the 2-in. x 5-in. area in the No. 1 rotor because of the following similarities.

1. The greenish-yellow silicates observed in the "woody area" following the burst were similar to those observed at the surface exposed by pulling apart a section of the inclusions in the No. 3 rotor.

2. The surface configuration of the 2-in. x 5-in. area of No. 1 was similar to the exposed surface of the 1 1/2-in. x 8-in. plane in No. 3, although coarser in nature.

3. The surface of the 2-in. x 5-in. area in No. 1, and the metal interface adjacent to the plane of inclusions in No. 3, were predominately intergranular in nature.

4. Both the 2-in. x 5-in. area in rotor No. 1, and the plane of inclusions in the No. 3 rotor are located along the centerline in the main body and about the same axial distance from the end of the body. In addition, these areas are toward the top of the ingots from which the forgings were made. It should be noted that the top part of the ingot was the exciter end of No. 1, and the top of the ingot was the turbine end of No. 3.

5. Both rotors showed minor sonic indications from the areas of the inclusions when tested before service, but in neither case was the size of sonic indications indicative of the size of inclusion present.

SUMMARY AND CONCLUSIONS

From the foregoing similarities between Pittsburg No. 1 and No. 3, we conclude that a plane of inclusions existed in No. 1 like that observed in No. 3. An inclusion array of such size, shape and low strength undoubtedly causes a severe stress concentration in the metal around the edges of the inclusion area, and it appears likely, from the results of bursting tests of large disks containing cracks, or notches at center bore holes, that such an inclusion array was the primary cause of the No. 1 rotor burst. Two questions remain:

1. Why did the sonic test before service give no indication of anything nearly as large as these inclusions?

2. Why did No. 1 burst, when No. 3 did not?

With regard to the sonic test, we are accumulating evidence that thin non-metallic inclusions if well bonded to the metal may transmit sonic waves quite effectively even though they cover relatively large planar areas, so that the reflections from them as observed on the sonic-test oscilloscope are considerably less than those coming from thick inclusions or thin cracks much smaller in area. This subject will be discussed in greater detail in another paper, "Ultrasonic Detection of Thin Laminar Inclusions" which is being presented at this meeting.

As to why No. 1 burst and No. 3 did not, the following facts are significant:

1. No. 1 had a higher V-notch Charpy transition temperature in the region of the inclusion than did No. 3. These transition temperatures were 210 F for No. 1 and 140 F for No. 3. The effect of lower transition temperature appears to be shown by spin tests on large-diameter severely notched disks from rotors having different transition temperatures. In these tests, the bursting strengths increase with decreased transition temperatures.

2. The radial width of the inclusion array in the No. 1 was slightly larger than that in No. 3. (2 inches versus 1 1/2 inches.)

3. The microstructure surrounding the "woody area" in Pittsburg No. 1 consisted primarily of coarse-grained upper bainite as shown in Fig. 11, while the microstructure in the vicinity of the large inclusion in No. 3 consists of a mixture of tougher fine-grained ferrite and some bainite as shown in Fig. 16.

4. The levels of ambient temperatures during the outages of Pittsburg No. 3 were probably higher than those which prevailed in the last outage preceding the burst of the No. 1 generator rotor. In addition, the No. 3 rotor was prewarmed before startup in the period following the No. 1 burst in March and disassembly from the stator for sonic retest in November 1956.

FORGING INSPECTION

To explore the possibility that there may be other rotors in service containing plate-like inclusions covering a relatively large area like those present in the Pittsburg No. 1 and No. 3 rotors, approximately 50 generator rotors have been selected for sonic retest at the owners' convenience. It is expected that if there are large planes of inclusions in any of these rotors similar to that in Pittsburg No. 3, they will show as larger indications on sonic retest than they did originally, as was the case on the Pittsburg No. 3. The rotors selected for sonic retest have been in service two or more years. Some of them are similar to the Pittsburg rotors in number or size of sonic indications reported in the original

factory tests. Others were chosen to retest bored as well as unbored rotors and forgings produced by different manufacturers employing different melting and heat-treating practices. Of this selected group, 22 unbored rotors have been re-examined with 17 showing no significant change in magnitude of indications. The other 5 rotors, including Pittsburg No. 3 previously mentioned, showed a change in magnitude of indications and were bored to remove the sonic indications.

A significant addition to the thorough inspection of large generator rotor forgings at the factory is a sonic re-examination following balancing at operating speed and overspeed tests. We believe this will show up large inclusion arrays if they exist. No changes in magnitude of sonic indications have been found to date on approximately 40 rotors so examined.

FORGING IMPROVEMENT

The results of this investigation re-emphasize the need for improvement of the homogeneity and toughness of large rotors. Work in this direction had been underway for three years when analysis of an earlier burst indicated a need for improvement of rotor forgings in three major respects:

1. Quality – or freedom from porosity, hydrogen flakes, thermal cracks.

2. Homogeneity – or freedom from inclusions, segregations, variations in grain structure.

3. Toughness – or the ability of the material to resist the initiation and propagation of cracks.

Significant progress has been made toward all of these objectives with the able assistance and excellent co-operation of the large forging suppliers. To improve quality, our sonic acceptance guides were tightened and published (Ref. 1). The steel mills have effectively met these stricter requirements and at the same time have reduced the number of forging rejections.

Homogeneity can be improved by changing from acid to basic steel-making practice, thereby reducing the amounts of the undesirable elements, sulphur and phosphorous. However, basic electric-furnace steels contain more hydrogen which tends to cause flaking during processing of the forging. Control of hydrogen has been difficult, but now, by pouring the basic electric steel in vacuum, most of the hydrogen can be removed and cleaner more homogeneous steel obtained. Several forgings from vacuum-poured ingots have now been obtained and more equipment for vacuum pouring of large ingots is being installed by the steel companies. Consumable electrode melting possibly is a further improvement for the future.

Toughness is the ability of a material to resist the initiation and propagation of brittle cracks from stress raisers and serves as insurance against uncontrollable factors and contingencies in the production of forgings and the manufacture of rotors.

Considerable effort has been expanded in developing a suitable measure of a material's toughness. The results of notched-bend, V-notch Charpy and bursting tests of internally notched disks have shown that the V-notch Charpy fracture-appearance transition temperature affords a good measure of the toughness of a material in the form of large notched disks. Thus transition temperature is a good guide for the evaluation, selection and acceptance of materials for rotors.

The correlation between notch-bend tests conducted at room temperature on 3-in. square specimens and V-notch Charpy fracture-appearance transition temperature was shown in a previous ASME paper (Ref. 2). The data shows that as transition temperatures decrease, the notch-bend strengths increase markedly. Since the test specimens had similar tensile strengths, the higher bend strengths indicate greater toughness.

Similarly the ratio, average bursting stress tensile strength, of large internally notched disks is higher for those materials with the lower V-notch Charpy transition temperature. These tests were made at room temperature on materials whose transition temperatures ranged from somewhat below to about 200 F above room temperature. The disks were cut from rotor forgings and were 19 inches to 24 inches in diameter, 2 inches to 6 inches thick, with 3-in. to 4-in. diameter bore holes having 1-in. deep sharp V-notches diametrically opposite.

In addition to showing the increase in toughness with lower transition temperatures, the disk-bursting tests also show an increase in toughness with increasing test temperature. This is illustrated in Fig. 18, which is a plot of disk temperature and the

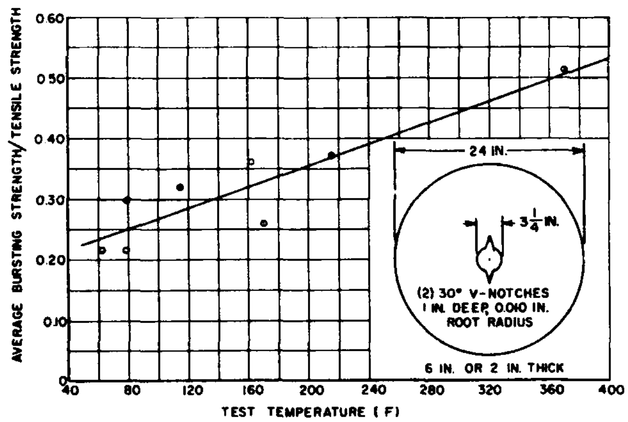


Fig. 18. Bursting strengths of notched disks as a function of temperature

ratio of average bursting stress to tensile strength of internally notched disks like those described, and having a transition temperature of 225 F. The curve shows a progressive increase in bursting strength from the lower to the higher temperatures. This increase is 20 to 30 percent over the temperature range of 70 F to 150 F. Because of this gain in strength and toughness with temperature, prewarming before startup of the larger and more highly stressed rotors has been recommended. The prewarming is carried out at reduced speeds until the rotor temperature is raised to approximately plus 150 F. The rotor is then brought to normal running speed.

An intensive study of the metallurgical factors affecting transition temperature has indicated that alloy composition, and/or heat treatment play the most important roles in controlling transition temperatures of large forgings. To obtain lower transition temperatures, we have concentrated our efforts in two major programs. One of these programs involves the evaluation of some thirty full-sized development rotors of different alloy composition, heat treatment, and/or steel-making practice. The other program involves modification of composition and heat treatment of current production forgings so as to produce a fine-grained bainite-ferrite structure which is less notch sensitive than the coarse-grained bainite structure.

All of the aforementioned items concerning quality, homogeneity and toughness will be discussed in greater detail in two papers to be presented at the 1957 annual ASME meeting (Ref. 3 and 4).

REFERENCES

1. ASME Paper No. 55-A-194, "Acceptance Guides for Ultrasonic Inspection of Large Rotor Forgings" by A. W. Rankin and C. D. Moriarty.

2. ASME Paper No. 55-A-208, "Report of the Investigation of Two Generator Rotor Fractures" by C. Schabtach, A. W. Rankin, E. L. Fogleman, D. W. Winne.

3. "Progress in the Development of Turbine-Generator Rotor Materials" by D. R. DeForest, D. L. Newhouse and B. R. Seguin.

4. "Application of the Griffith-Irwin Theory of Crack Propagation to the Bursting Behavior of Rotors, Including Analytical and Experimental Studies" by D. H. Winne and B. M. Wundt.